# Infinity and Finiteness in Strings and Geometry

- 2603.02304 [hep-th] with **Fabio Mantegazza, Enrico Marchetto, Elli Pomoni, Thorben Skrzypek**

- 2603.24666 [math.AG] with **Antonella Grassi, Rick Miranda, Kapil Paranjape, Vasudevan Srinivas**

**Timo Weigand, Strings and Geometry, Uppsala, May 21, 2026**

Universität Hamburg
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DFG German-Israeli Project Cooperation (DIP)
Holography and the Swampland

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# Two hallmarks of Quantum Gravity

**Infinite** gravitational towers
**asymptotically** in moduli space:

Swampland Distance Conjecture
**[Ooguri,Vafa'06]**

**Swampland Program / Quantum Gravity**

**Finiteness** of
light, gravitational
degrees of freedom in
**interior** of moduli space

see talk by D. Prieto

Duality **[Ooguri,Vafa'06]** /
Emergent String Conjecture
**[Lee,Lerche,TW'19]**

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*Part I:*
Nature of towers in AdS:
**Partial weak coupling limits in 4d N=2**

*Part II:*
Bounds on MW group of elliptic fibrations:
**Math proofs and new results**

# Two hallmarks of Quantum Gravity

**Infinite** gravitational towers **asymptotically** in moduli space:

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Nature of towers in AdS:

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**STRINGS & GEOMETRY**

**Finiteness** of light, gravitational degrees of freedom in **interior** of moduli space

*Part II:*
Bounds on MW group of elliptic fibrations:

**Math proofs and new results**

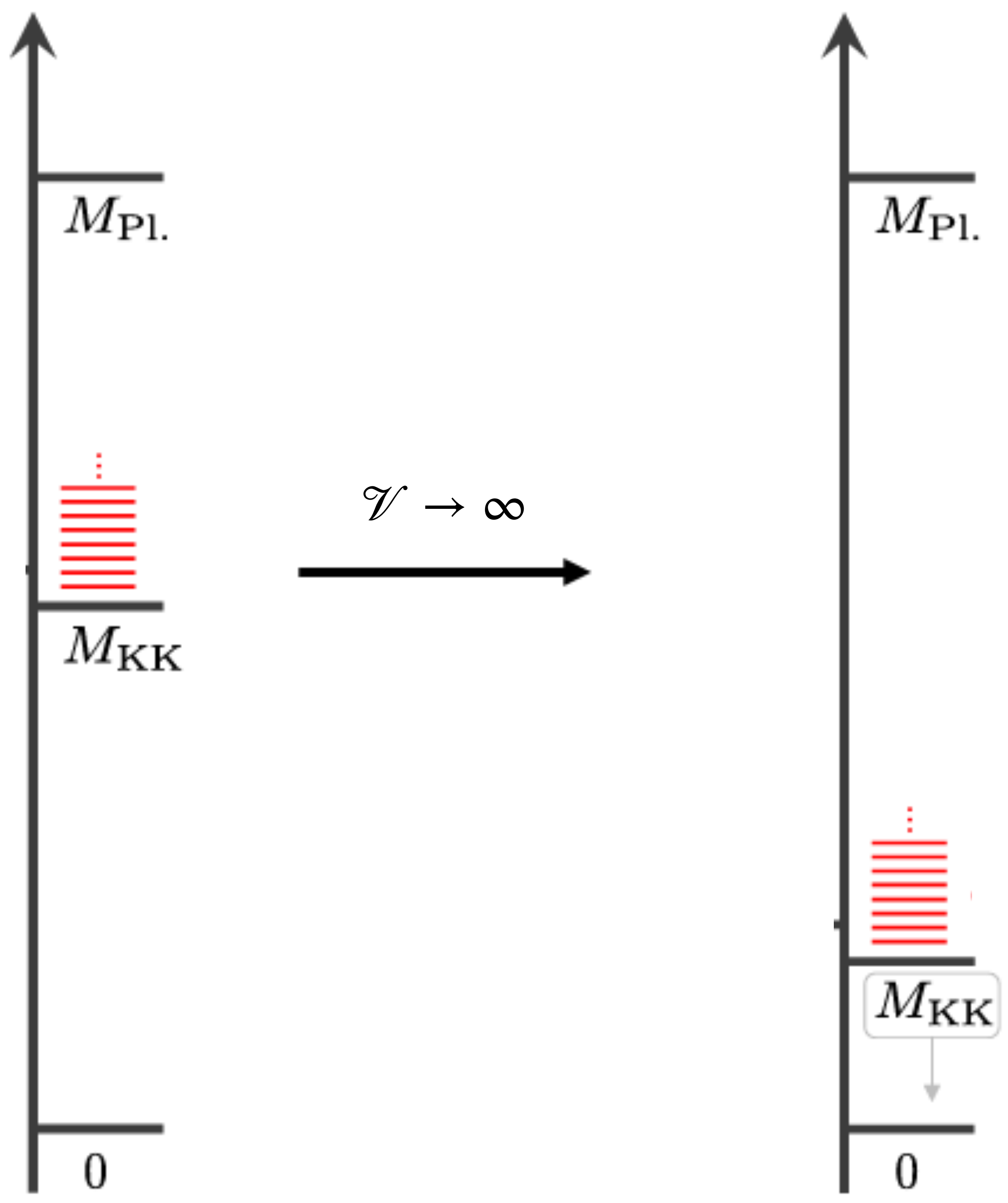
## *Part I:*

# String Towers in AdS gravity

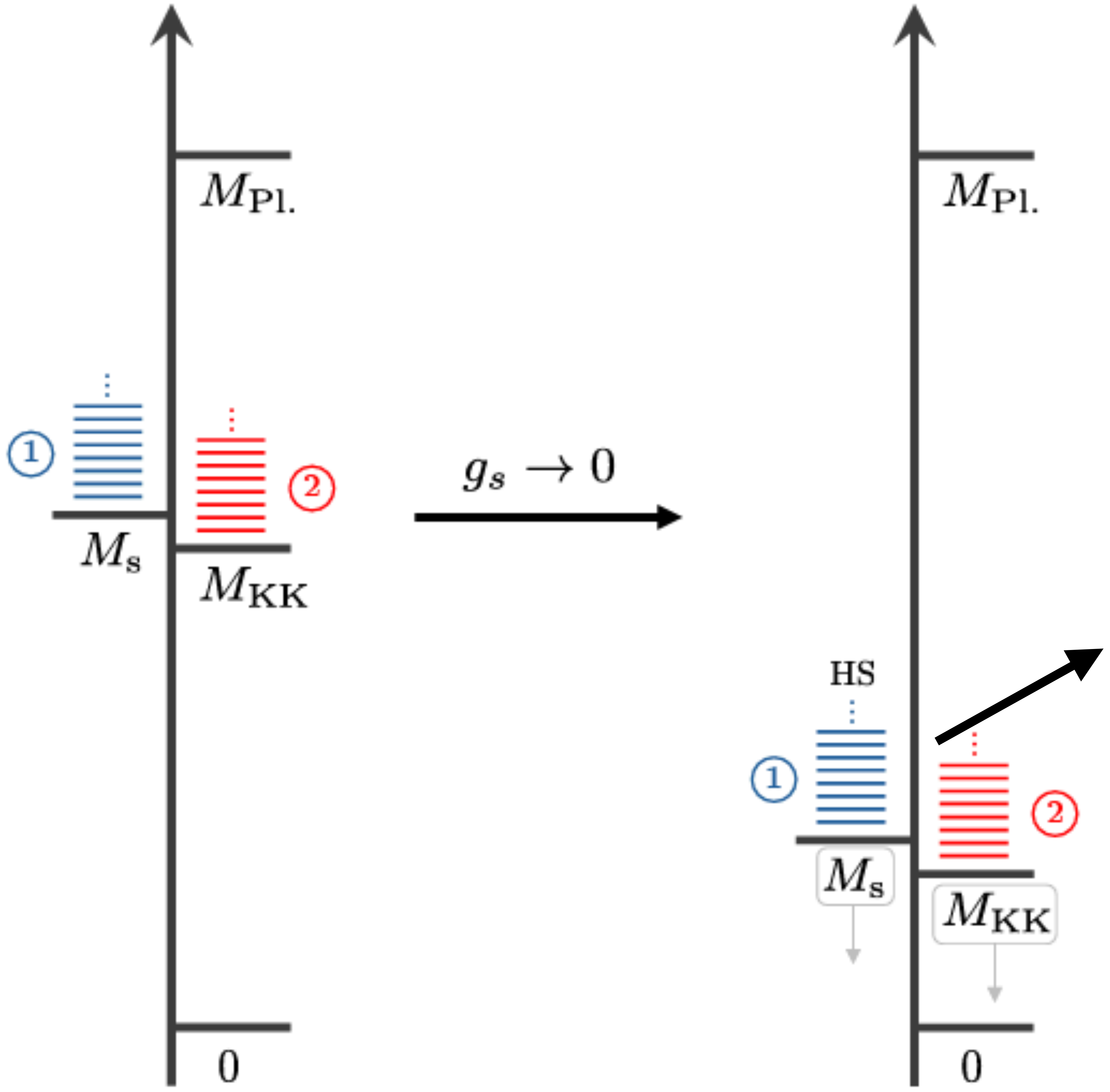
[Mantegazza,Marchetto,Pomoni,Skrzypek,TW’26]

# Infinite distance limits in flat space gravity

## Decompactification limit




## Emergent string coupling




**String tower:**

- fundamental string
- parametrically at KK scale
- exponential degeneracy:

$$d \sim e^{c\, m}$$

# What is the analogue in $\mathrm{AdS}_{d+1}$?

**Infinite distance directions via dual $\mathrm{CFT}_d$ (conformal manifold)**

**CFT Distance Conjecture:** **[Perlmutter,Rastelli,Vafa,Valenzuela'20] [Baume,Calderon-Infante'20]**

$d \geq 3$**:** Infinite Distance loci are weak coupling and give rise to towers of higher-spin (HS) currents.

- Proof of HS →weak coupling: **[Baume, Calderon-Infante'23]**
- Detailed study in overall weak coupling limits: **[Calderon-Infante,Valenzuela'24] [Calderon-Infante, Mohseni'26] [Baume,Mantegazza-to appear]**

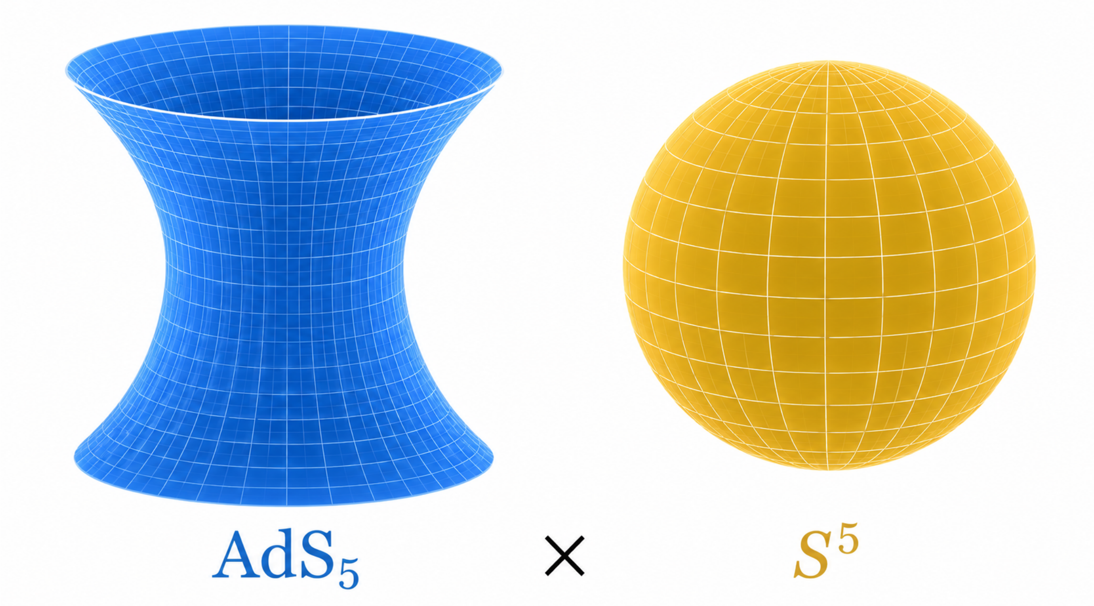
⇝ **talk by Irene Valenzuela**

**This talk:**

- Mixed weak coupling limits and
- comparison to emergent strings in flat space

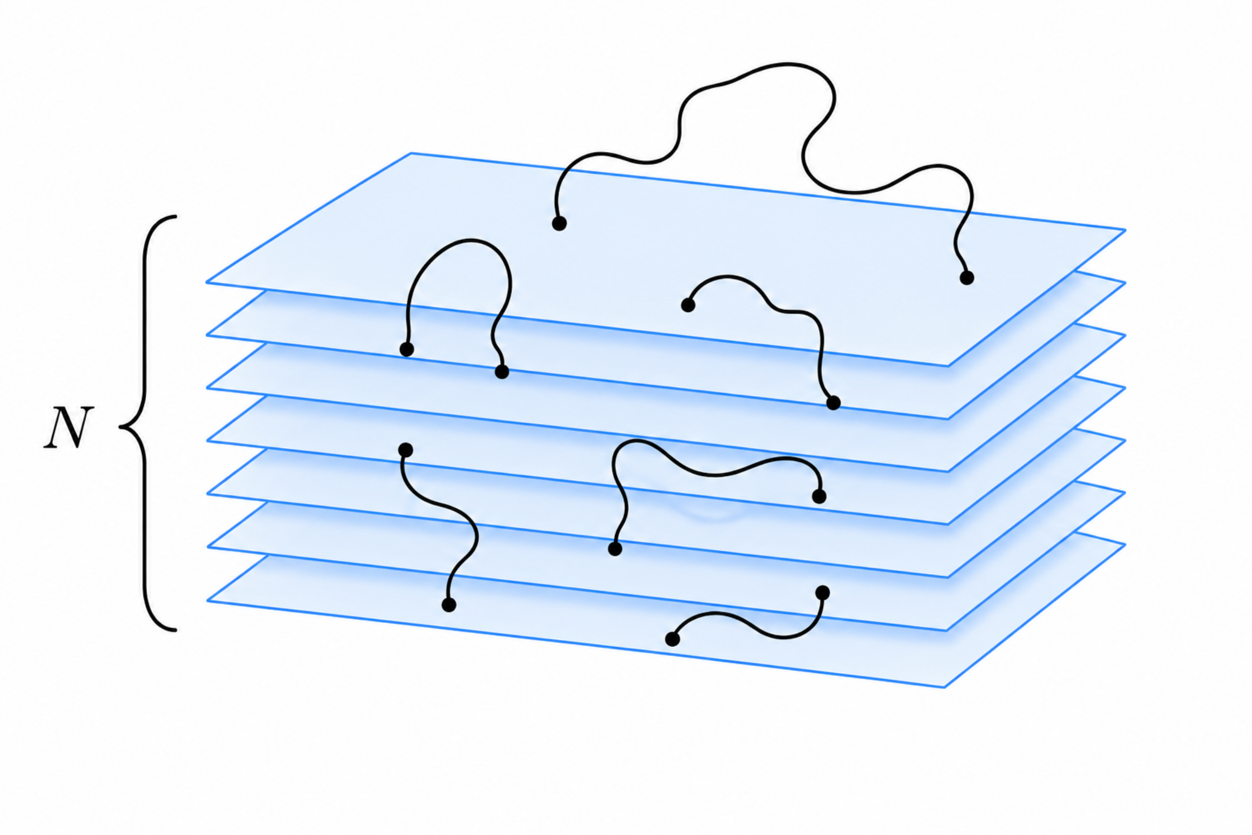
# Reminder: $\mathrm{AdS}_5 \times S^5$

Type IIB on $\mathrm{AdS}_5 \times S^5$




$\Longleftrightarrow$

$N = 4$ SYM on $\mathbb{R}^{1,3}$




5d Planck scale $M_{\mathrm{Pl},5}$

AdS scale $M_{\mathrm{AdS}} \sim \ell_{\mathrm{AdS}}^{-1}$

String scale $M_s \sim \ell_s^{-1}$

rank $N$

**modulus:** 't Hooft coupling $\lambda = g_{\mathrm{YM}}^2 N$

$$\lambda = 4\pi g_s N \sim \frac{M_s^4}{M_{\mathrm{AdS}}^4}$$

$$\frac{M_{\mathrm{AdS}}^3}{M_{\mathrm{Pl}}^3} \sim \frac{1}{N^2}$$

$N \gg 1$, fixed

# Reminder: $AdS_5 \times S^5$

$$\frac{M_s^4}{M_{\rm AdS}^4} \sim \lambda \gg 1$$ **effective supergravity regime**

**States via (strongly coupled) dual CFT:**

$$\frac{m^2_{\rm bos}}{M^2_{\rm AdS}} = (\Delta - j - \bar{j} - 2)(\Delta + j + \bar{j} - 2)$$

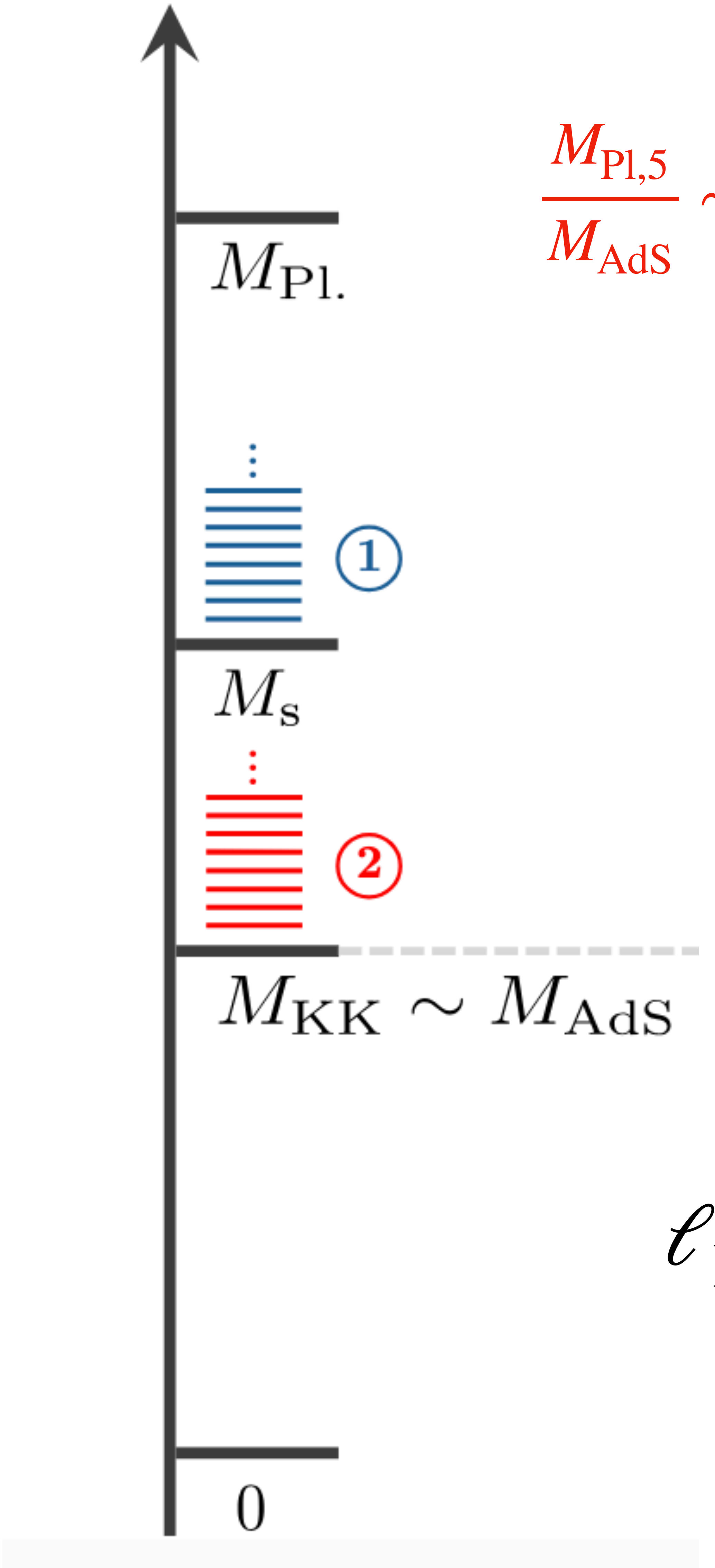
[Metsaev'03]

$(j, \bar{j})$: spin of dual SYM operator

$\Delta$ : conformal dimension of dual SYM operator

$$\Delta(\lambda) = \Delta_0 + \gamma(\lambda)$$

$\gamma(\lambda)$: anomalous conformal dimension




$$\frac{M_{\rm Pl,5}}{M_{\rm AdS}} \sim N^{2/3}, \qquad \frac{M_{\rm AdS}}{M_s} \sim \lambda^{-1/4}$$

**Type IIB string tower: exponential degeneracy**

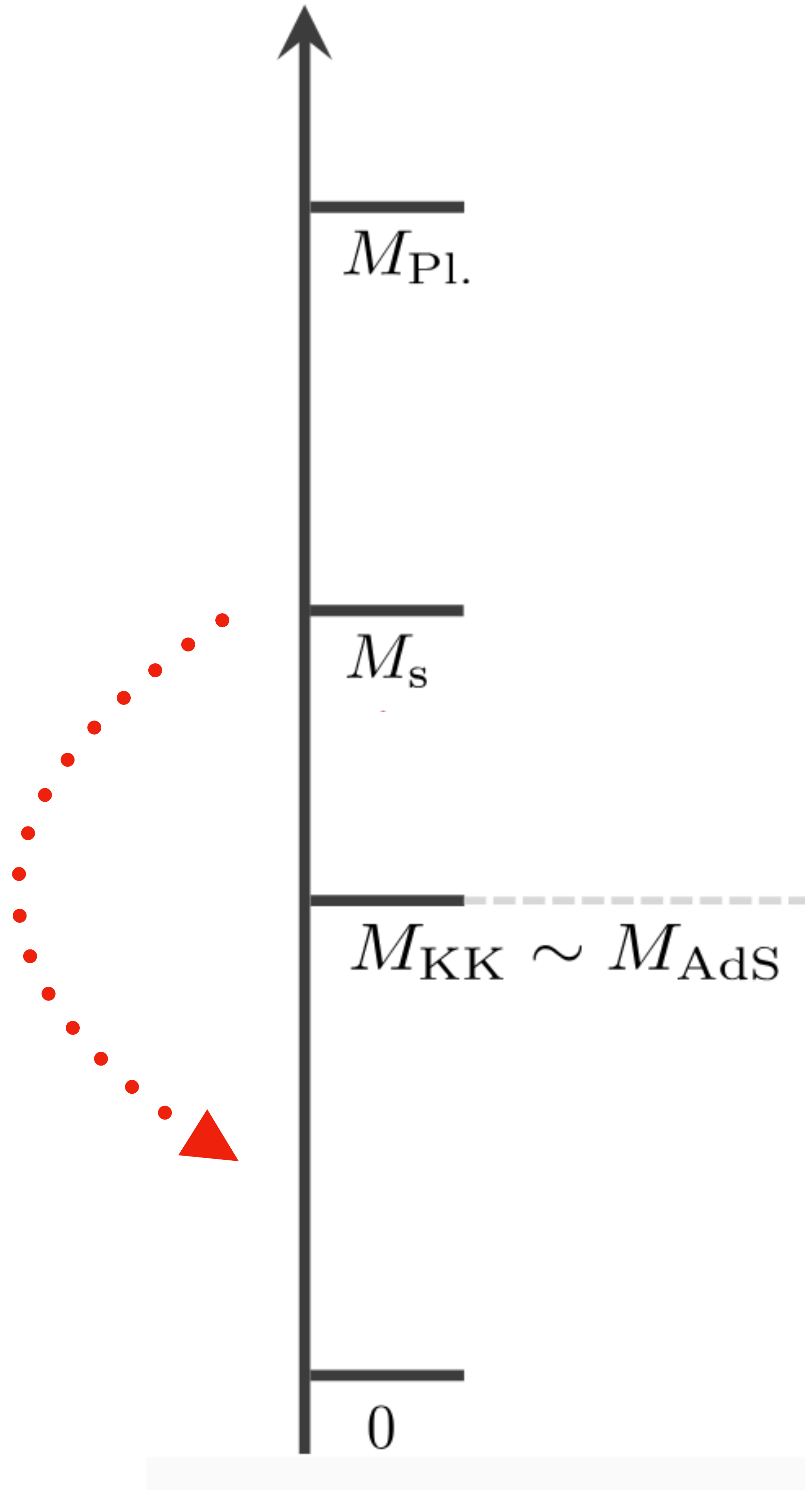
**SUGRA KK tower: polynomial degeneracy**

$$\ell_{\rm KK} \sim \ell_{S^5} \sim \ell_{{\rm AdS}_5}$$

# Weakly coupled string limit in AdS: N=4

$\frac{M_s^4}{M_{\rm AdS}^4} \sim \lambda \to 0$: **substringy regime:**

**Better described by dual weakly coupled CFT**



# Weakly coupled string limit in AdS: N=4

$$\frac{M_s^4}{M_{\text{AdS}}^4} \sim \lambda \to 0:$$ **substringy regime:** **Better described by dual weakly coupled CFT**

- **Define** an ``effective mass'':

$$\frac{m_{\text{eff.}}^2}{M_{\text{AdS}}^2} = (\Delta - j - \bar{j} - 2)(\Delta + j + \bar{j} - 2) \qquad \Delta(\lambda) = \Delta_0 + \gamma(\lambda) \to \Delta_0$$

- **Asymptotically massless states:**

$$\Delta_0 = 2 + J\,, \qquad j = \bar{j} = \frac{J}{2} \qquad \frac{m_{\text{eff.}}^2}{M_{\text{AdS}}^2} \sim 2J\lambda + \mathcal{O}(\lambda^2) \to 0$$

**Higher-spin tower**

$$\text{tr}[\phi^i \partial^J \phi_i] + \text{tr}[\bar{\lambda}^I \partial^{J-1} \lambda_I] + \text{tr}[\bar{F} \partial^{J-2} F]$$

**as predicted by CFT Distance Conjecture**

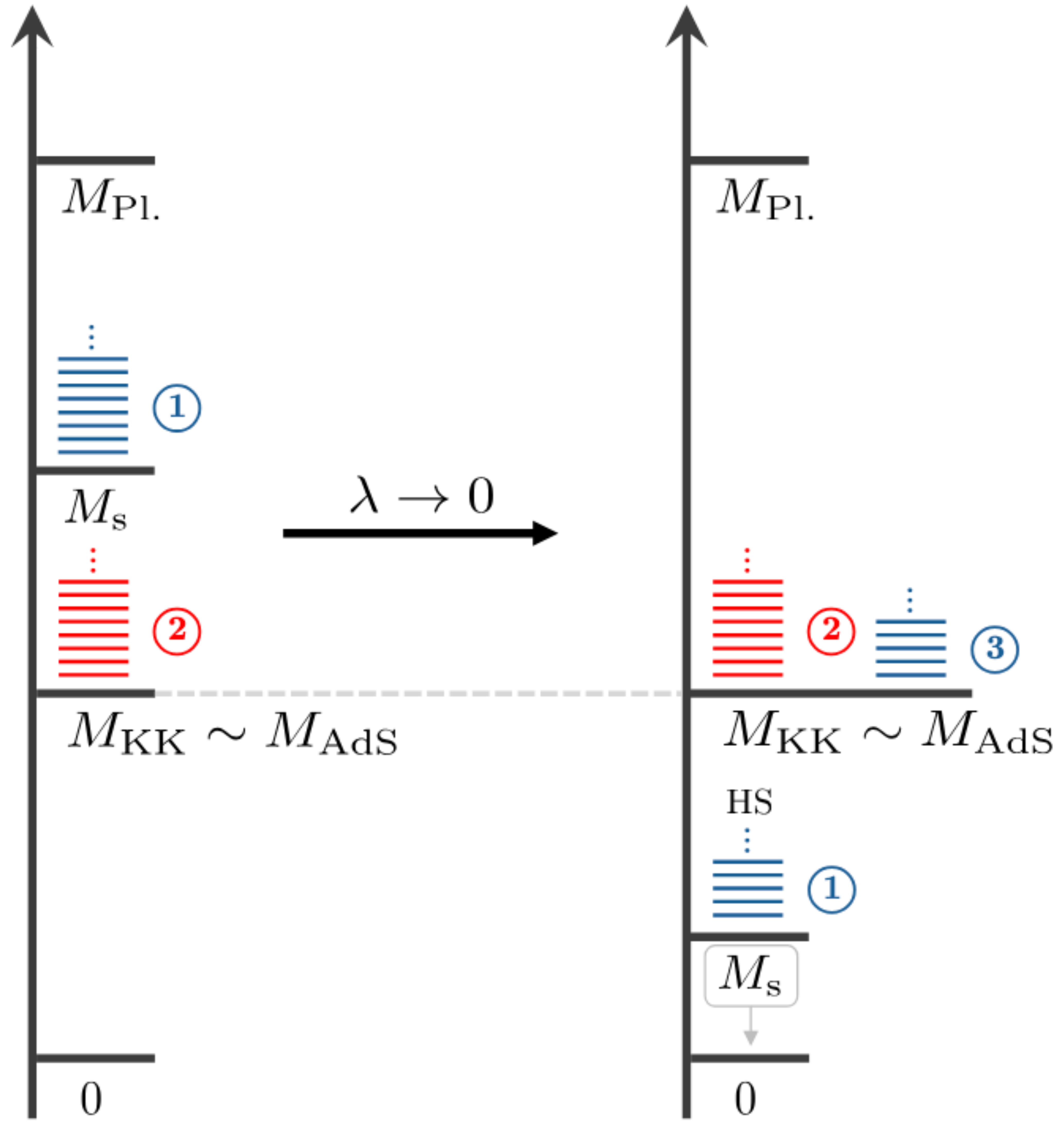
[Perlmutter,Rastelli,Vafa,Valenzuela'20]

[Baume,Calderon-Infante'20,'23]

- But: **Polynomial rather than exponential degeneracy**

$$\deg(m_{\text{eff.}}) \sim J^2$$

# Weakly coupled string limit in AdS: N=4




$$\frac{M_s^4}{M_{\rm AdS}^4} \sim \lambda \to 0:$$ **substringy regime**

③ **Remaining string tower of exponential degeneracy**

**exponential degeneracy, but stuck at AdS scale due to curvature**

$$\frac{m^2_{\rm eff.}}{M^2_{\rm AdS}} = (\Delta - j - \bar{\jmath} - 2)(\Delta + j + \bar{\jmath} - 2)$$

① **Higher spin tower (R-charge 0)**

**asymptotically massless, but only polynomial degeneracy**

# General mixed weak coupling limit in N=2

String theory on $\mathrm{AdS}_5 \times X$
with $N = 2$ **SUSY**

$\Longleftrightarrow$

Dual conformal manifold can be higher-dimensional
with **more general weak coupling limits**

gauge couplings:
$(g_1, g_2, \ldots, g_k)$

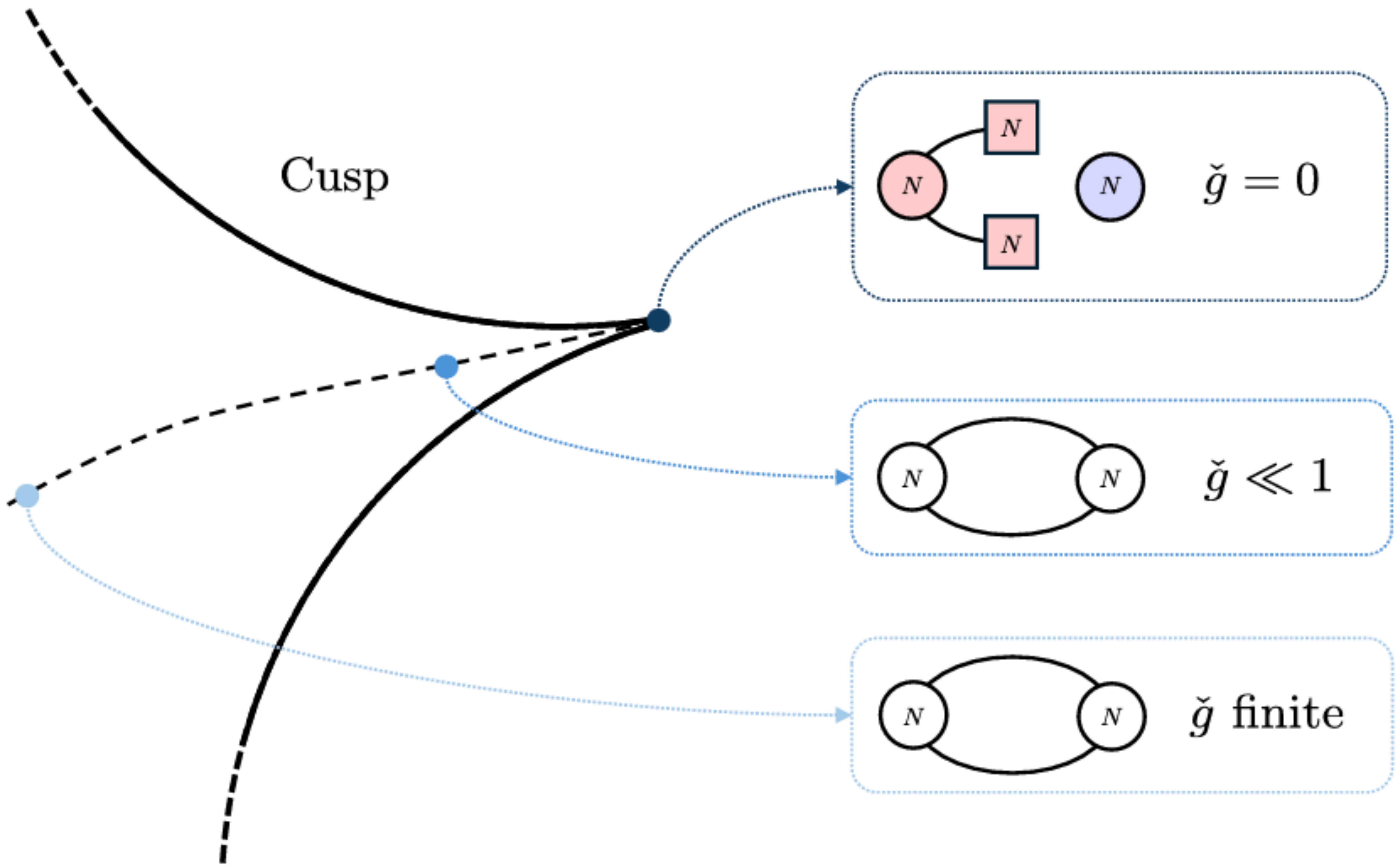
**overall free limit:**
all $g_i \to 0$

[Calderon-Infante,Valenzuela'24]
[Calderon-Infante, Mohseni'26]
[Baume,Mantegazza-to appear]

**see talk by Irene Valenzuela**

**mixed limit:**
$\check{g} := g_k \to 0,$
remaining finite

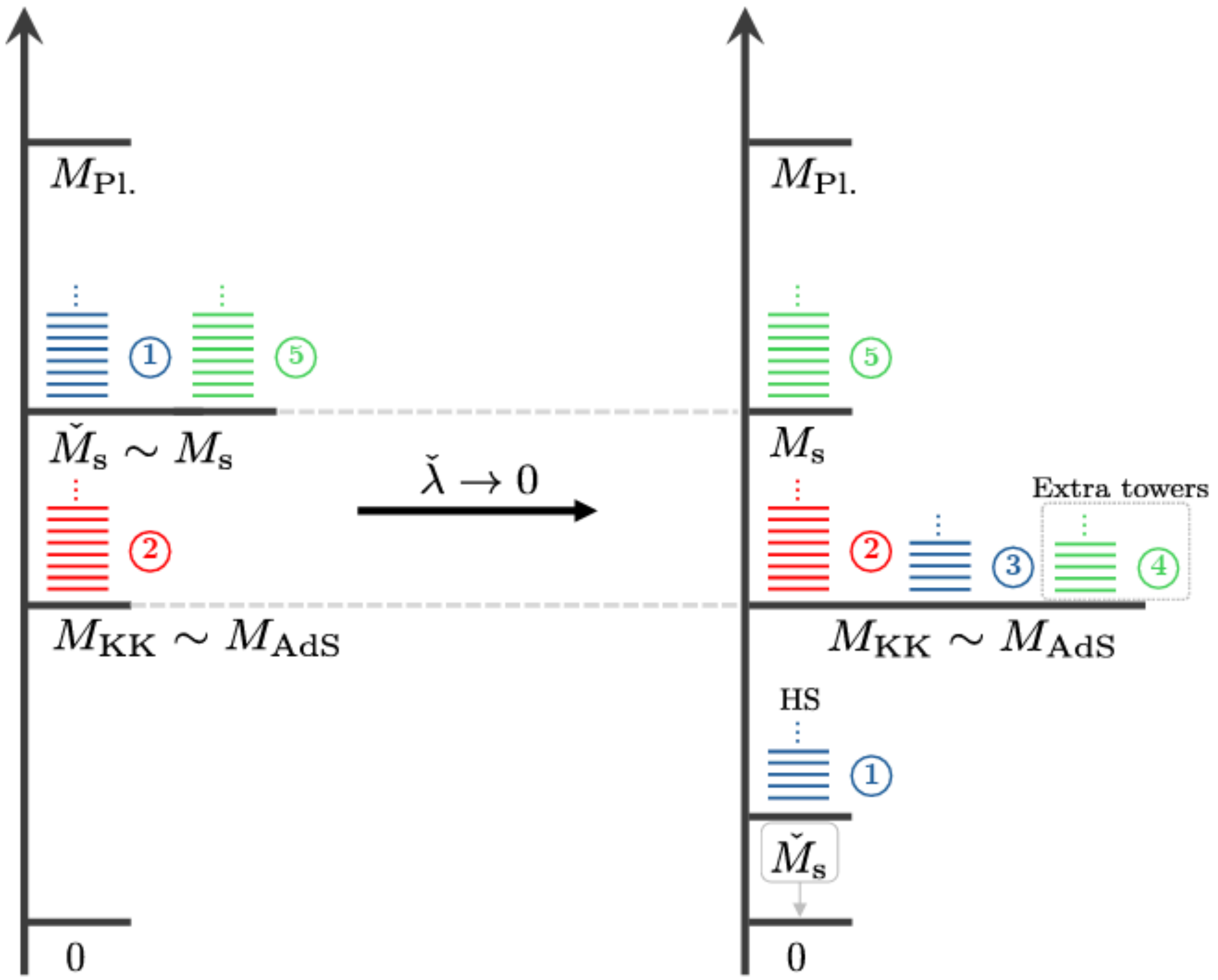
[Mantegazza,Marchetto, Pomoni,Skrzypek,TW'26]



# General mixed weak coupling limit

**Mixed limit: $\check{g} := g_k \to 0$, remaining finite**

**[Mantegazza,Marchetto, Pomoni,Skrzypek,TW'26]**




**Novelty from interacting sector:**

(4) extra, **interacting** tower at AdS scale,

**related to HS via SUSY**, of **exponential** degeneracy

**From asymptotically free sector:**

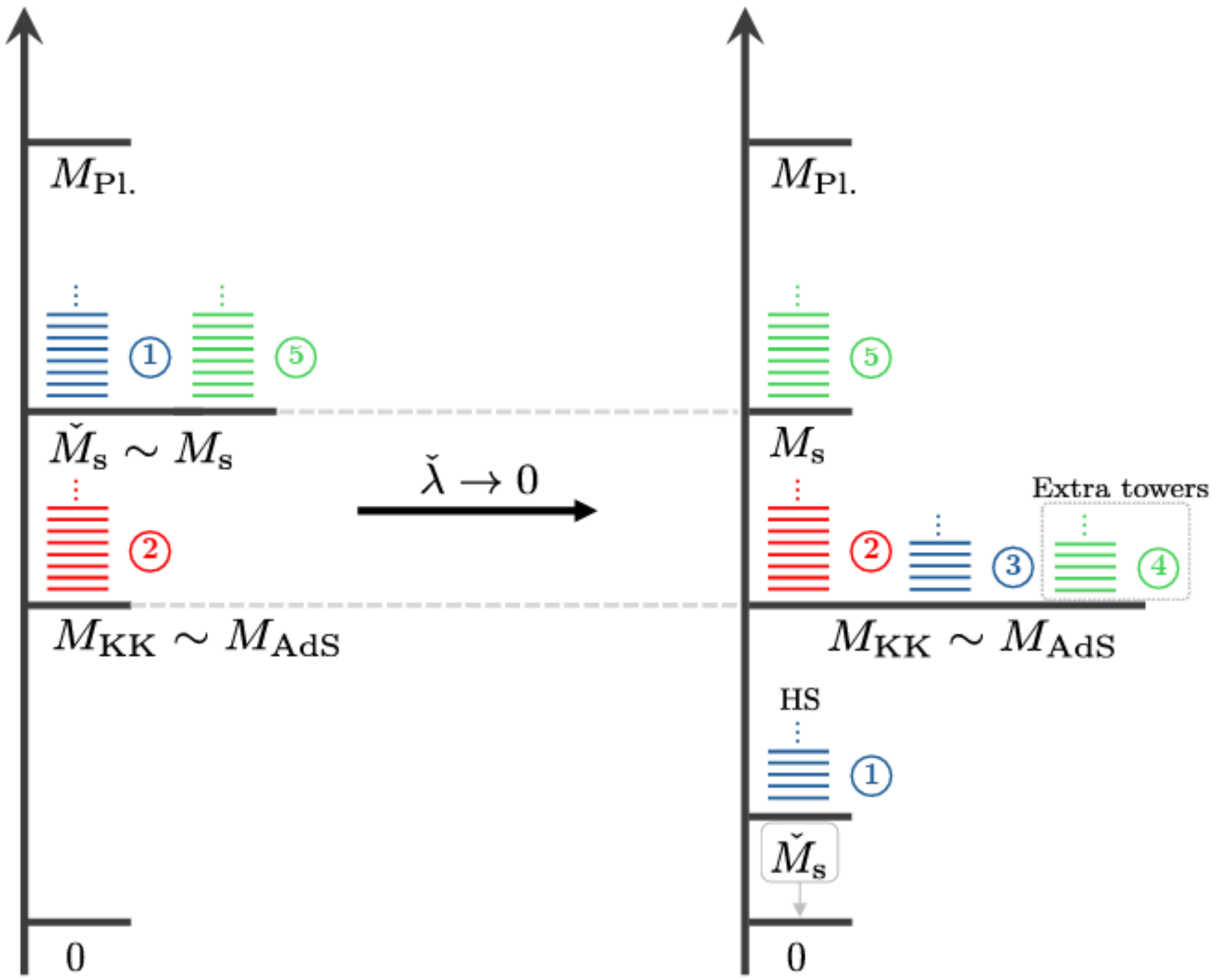
(1) free massless HS tower (polynomial)

(3) accompanied by free exponential tower at AdS scale

# General mixed weak coupling limit

**Mixed limit:** $\check{g} := g_k \to 0$, **remaining finite**

[Mantegazza,Marchetto, Pomoni,Skrzypek,TW'26]




**Novelty from interacting sector:**

4 extra, **interacting** tower at AdS scale, **related to HS via SUSY**, of **exponential** degeneracy

**Key point:**

This is a consequence of representation theory only!

# Extra tower from recombination rule

**Mixed limit:** $\check{g} := g_k \to 0,$ **remaining finite in 4d N=2 SCFT**

**Long superconformal multiplet:** $\mathscr{A}^{\Delta}_{R,r(j,\bar{j})}$

R-symmetry: $SU(2)_R \times U(1)_r$

Suppose a multiplet hits **extremality bound**

$$\check{g} \to 0 : \quad \Delta \to 2 + 2j + 2R + r \quad \text{and/or} \quad \Delta \to 2 + 2\bar{j} + 2R - r$$

**Long multiplet** $\xrightarrow{\check{g} \to 0}$ **Short BPS multiplets**

**Recombination rules**

[Dolan,Osborn'02] [Gadde,Pomoni,Rastelli'09]

E.g.

$$\mathscr{A}^{2R+j+\bar{j}+2}_{R,\,\bar{j}-j\,(j,\bar{j})} \simeq \hat{\mathscr{C}}_{R(j,\bar{j})} \oplus \hat{\mathscr{C}}_{R+\frac{1}{2}\,(j-\frac{1}{2},\bar{j})} \oplus \hat{\mathscr{C}}_{R+\frac{1}{2}\,(j,\bar{j}-\frac{1}{2})} \oplus \hat{\mathscr{C}}_{R+1\,(j-\frac{1}{2},\bar{j}-\frac{1}{2})}$$

for

$\Delta \to 2 + 2j + 2R + r$ and $\Delta \to 2 + 2\bar{j} + 2R - r$

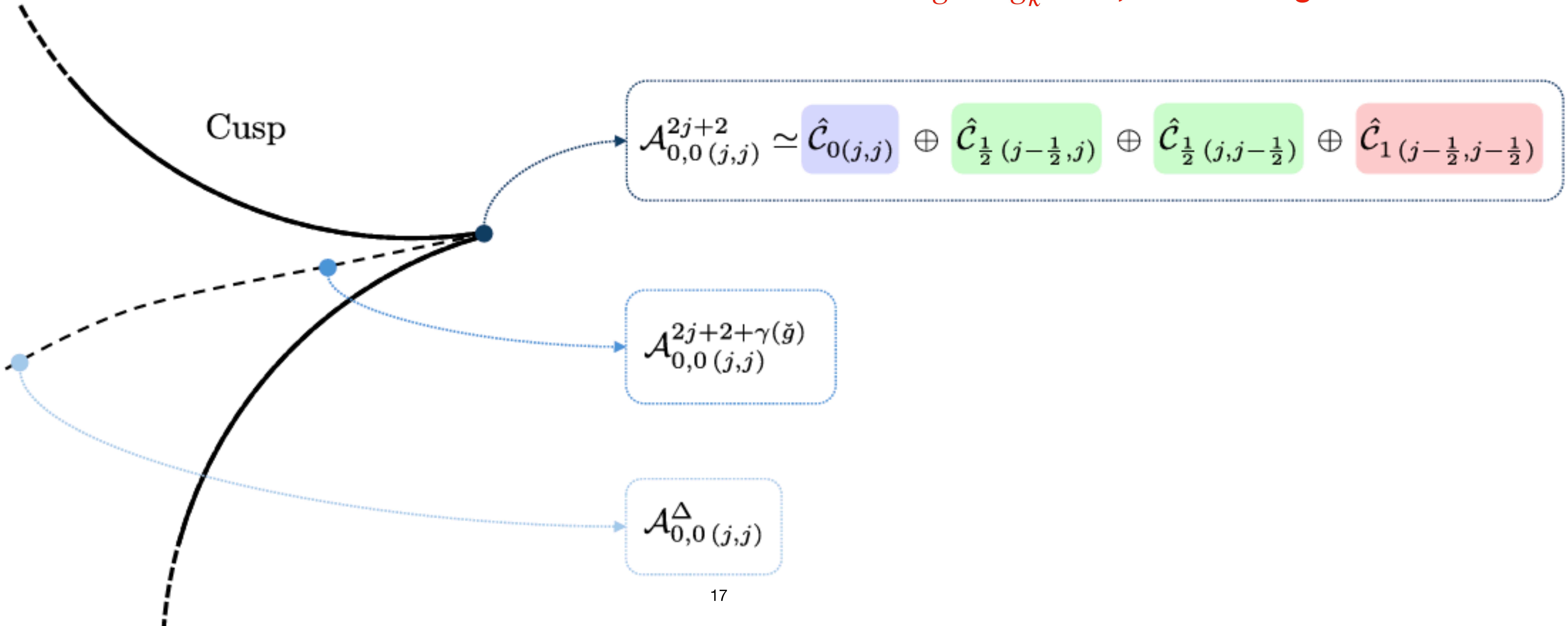
↓ short multiplet whose primary has

$r = j - \bar{j}, \quad \Delta = 2 + 2R + j + \bar{j}$

# Extra tower from recombination rule

Consider this recombination for $\mathscr{A}^{\Delta}_{0,0\,(j,j)}$:    Long multiplet with $R = 0 = r, \quad j = \bar{j}$

**in mixed limit:** $\check{g} := g_k \to 0$, **remaining finite**



# Extra tower from recombination rule

$$\mathrm{tr}[\check{\bar{\phi}}\partial^J\check{\phi}] + \mathrm{tr}[\check{\bar{\lambda}}^I\partial^{J-1}\check{\lambda}_I] + \mathrm{tr}[\check{\bar{F}}\partial^{J-2}\check{F}]$$

$\updownarrow$

$$\mathscr{A}^{2j+2}_{0,0\,(j,j)} \simeq \hat{\mathcal{C}}_{0(j,j)} \oplus \hat{\mathcal{C}}_{\frac{1}{2}\,(j-\frac{1}{2},j)} \oplus \hat{\mathcal{C}}_{\frac{1}{2}\,(j,j-\frac{1}{2})} \oplus \hat{\mathcal{C}}_{1\,(j-\frac{1}{2},j-\frac{1}{2})}$$

$\hat{\mathcal{C}}_{0(j,j)}$ ⋓ HS currents $\Rightarrow$ $\frac{m^2}{M^2_{\mathrm{AdS}}} = 0$

$\hat{\mathcal{C}}_{1\,(j-\frac{1}{2},j-\frac{1}{2})}$ ⋓ Extra states $\Rightarrow$ $\frac{m^2}{M^2_{\mathrm{AdS}}} = \mathcal{O}(1)$

[Dolan,Osborn'02]

[Gadde,Pomoni,Rastelli'09]

$\hat{\mathscr{C}}_{R(j,\bar{j})}$: short BPS multiplet

$r = j - \bar{j}, \quad \Delta = 2 + 2R + j + \bar{j}$

$\gamma = 0$ **due to BPS protection** - though **strongly coupled**

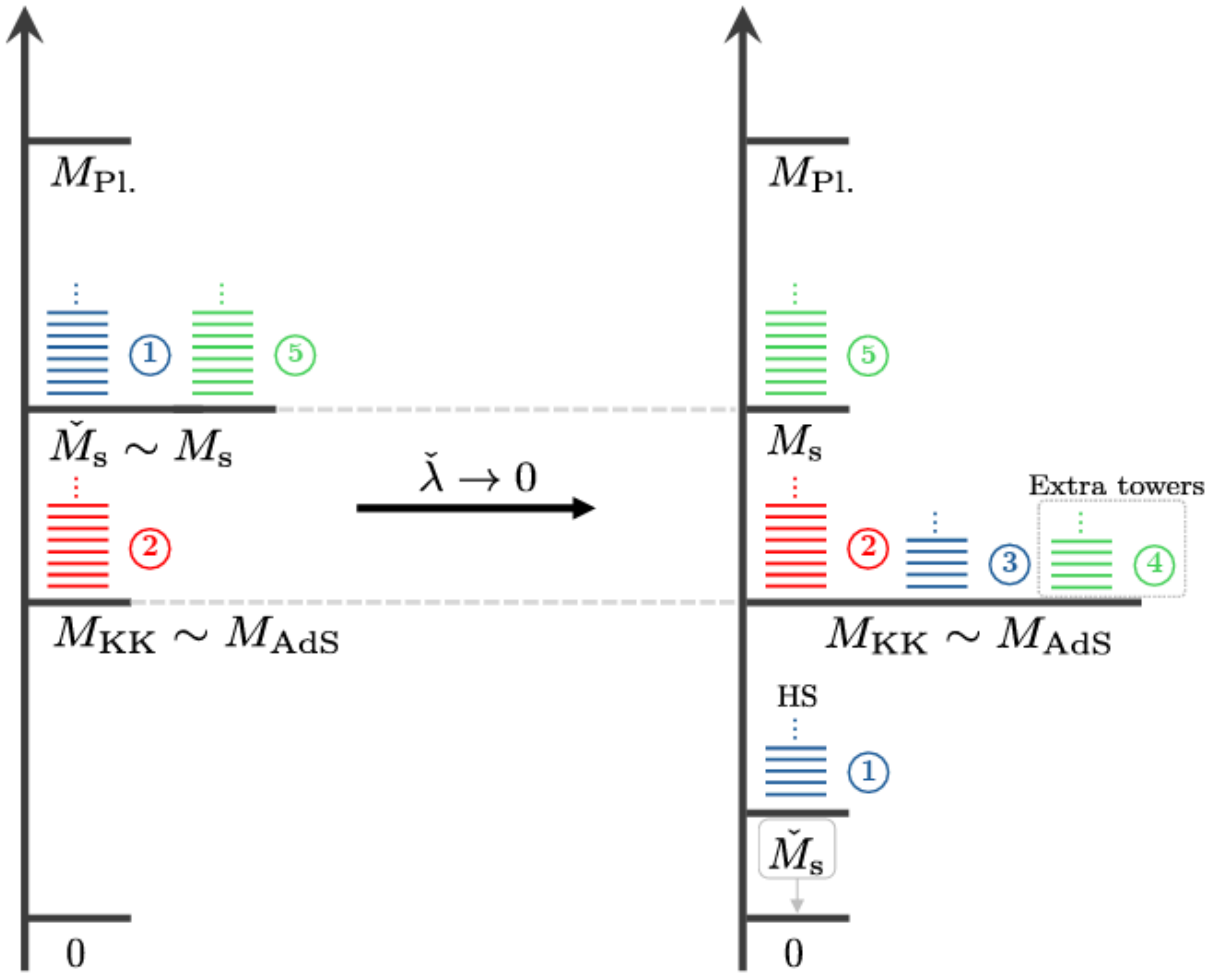
massive due to non-zero R-charge!

**free** — mixed — **interacting**

SUSY transformation

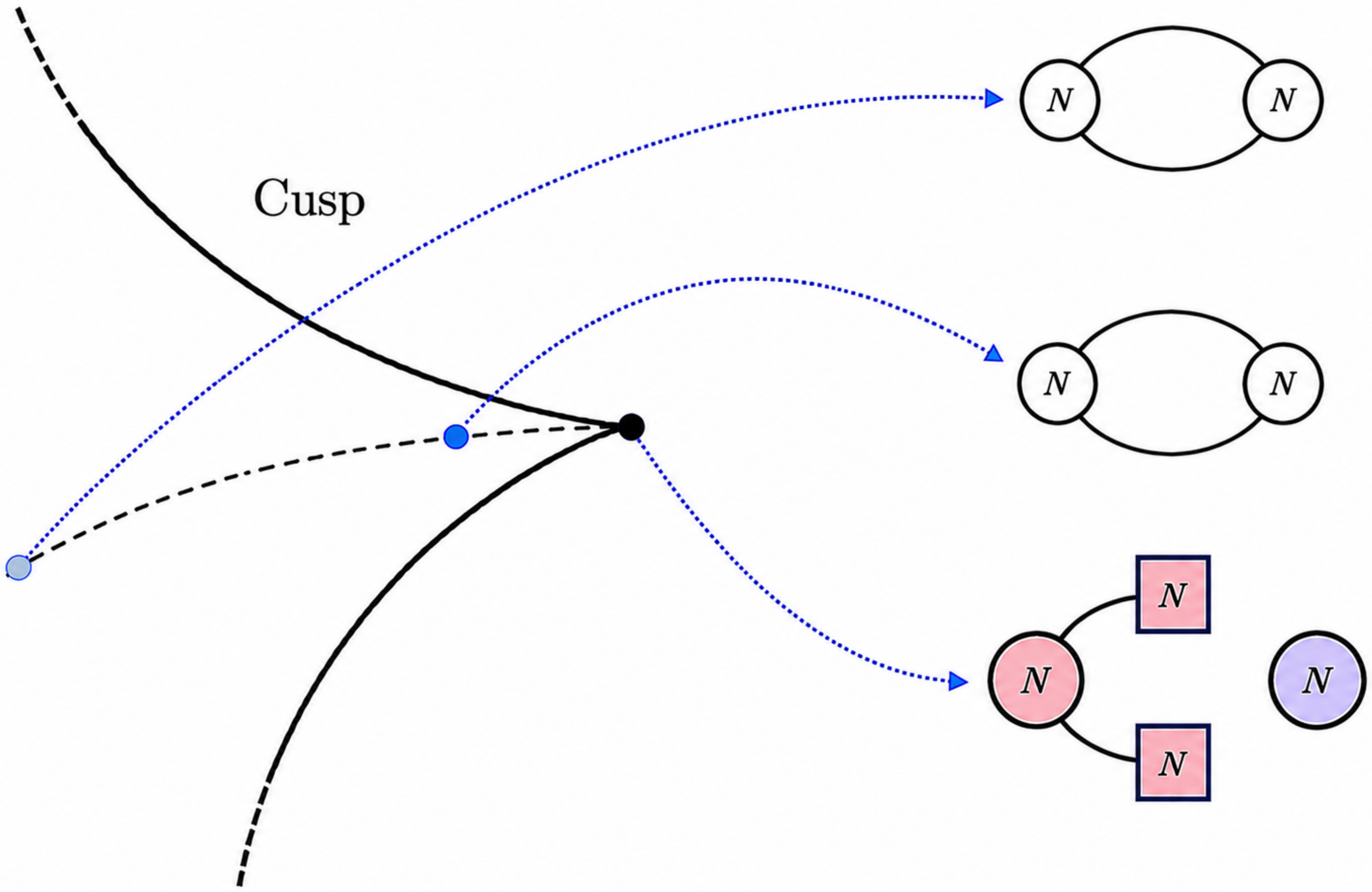
$$\mathcal{Q}(\check{g}) = \mathcal{Q}_0 + \check{g}\mathcal{Q}_1 + \ldots \qquad \check{\bar{\lambda}}\check{\lambda} \xrightarrow[\mathcal{Q}_1]{} \check{\bar{\lambda}}\check{\lambda}\check{\lambda} + \check{\lambda}\bar{Q}Q + \ldots \xrightarrow[\mathcal{Q}_1]{} \check{\bar{\lambda}}\check{\lambda}\check{\bar{\lambda}}\check{\lambda} + \check{\bar{\lambda}}\check{\lambda}\bar{Q}Q + \bar{Q}Q\bar{Q}Q + \ldots\,.$$

# Extra tower from recombination rule




[Mantegazza,Marchetto, Pomoni,Skrzypek,TW'26]

# Example: Two-node quiver gauge theory




**Orbifold theory**
$g = \check{g}$

**Interpolating theory**
$g$ fixed, $\hat{g} \to 0$

**SCQCD**
$\check{g} = 0,$
$g$ fixed

$$\mathrm{AdS}_5 \times S_5/\mathbb{Z}_2 =$$
$$\mathrm{AdS}_5 \times (S^1 \times S^3/\mathbb{Z}_2) \ltimes I$$
$U(1)_r$ $\quad SU(2)_R$

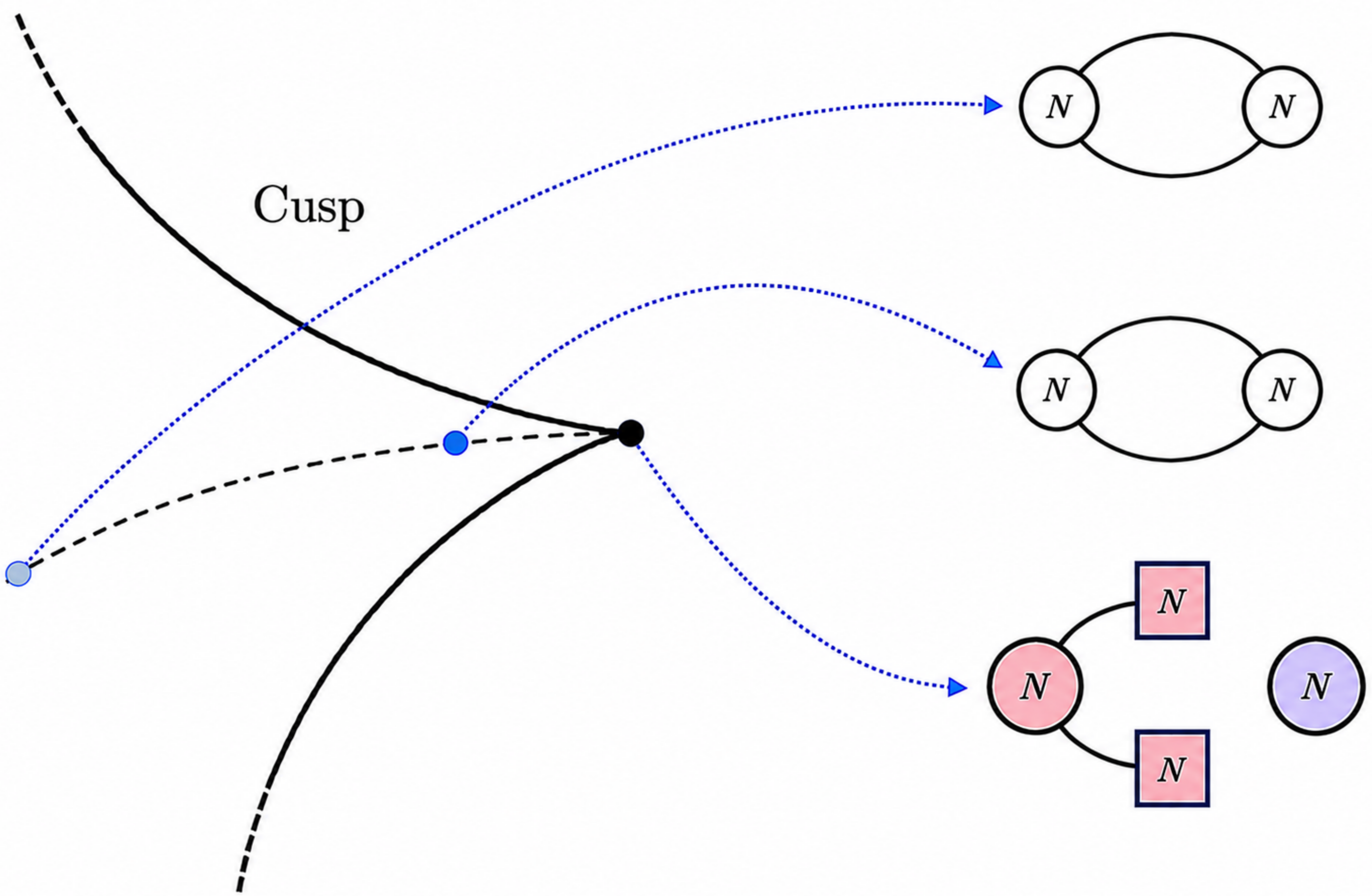
**Part of spectrum inherited from orbifold theory:**

**only R-singlets**
**``loss" of $S^3$ (non-critical string)**
**but still rooted in IIB superstring**

[Gadde,Pomoni,Rastelli'09]

# Example: Two-node quiver gauge theory

**Supersymmetric index:** $\mathcal{I} := \mathcal{I}^{L}(t, y, v) = \mathrm{Tr}(-1)^{F} t^{2(\Delta + j)} y^{2\bar{j}} v^{r-R}$




$\mathcal{I}_{\text{orbi}}$ known

$\mathcal{I}_{\text{inter}} = \mathcal{I}_{\text{orbi}}$

$\mathcal{I}_{\text{SQCD}}$ known

$\mathcal{I}_{\text{inheri}} = \mathcal{I}_{\text{orbi}}|_{\text{SQCD}}$ →

$$\Delta \mathcal{I} = \mathcal{I}_{\text{SCQCD}} - \mathcal{I}_{\text{inheri}}$$
$$\Delta \mathcal{I} \neq 0$$

**Origin of $\Delta \mathcal{I} \neq 0$:**

**Additional short multiplets**
**at $\check{g} \neq 0$**
**absent for $\check{g} > 0$**

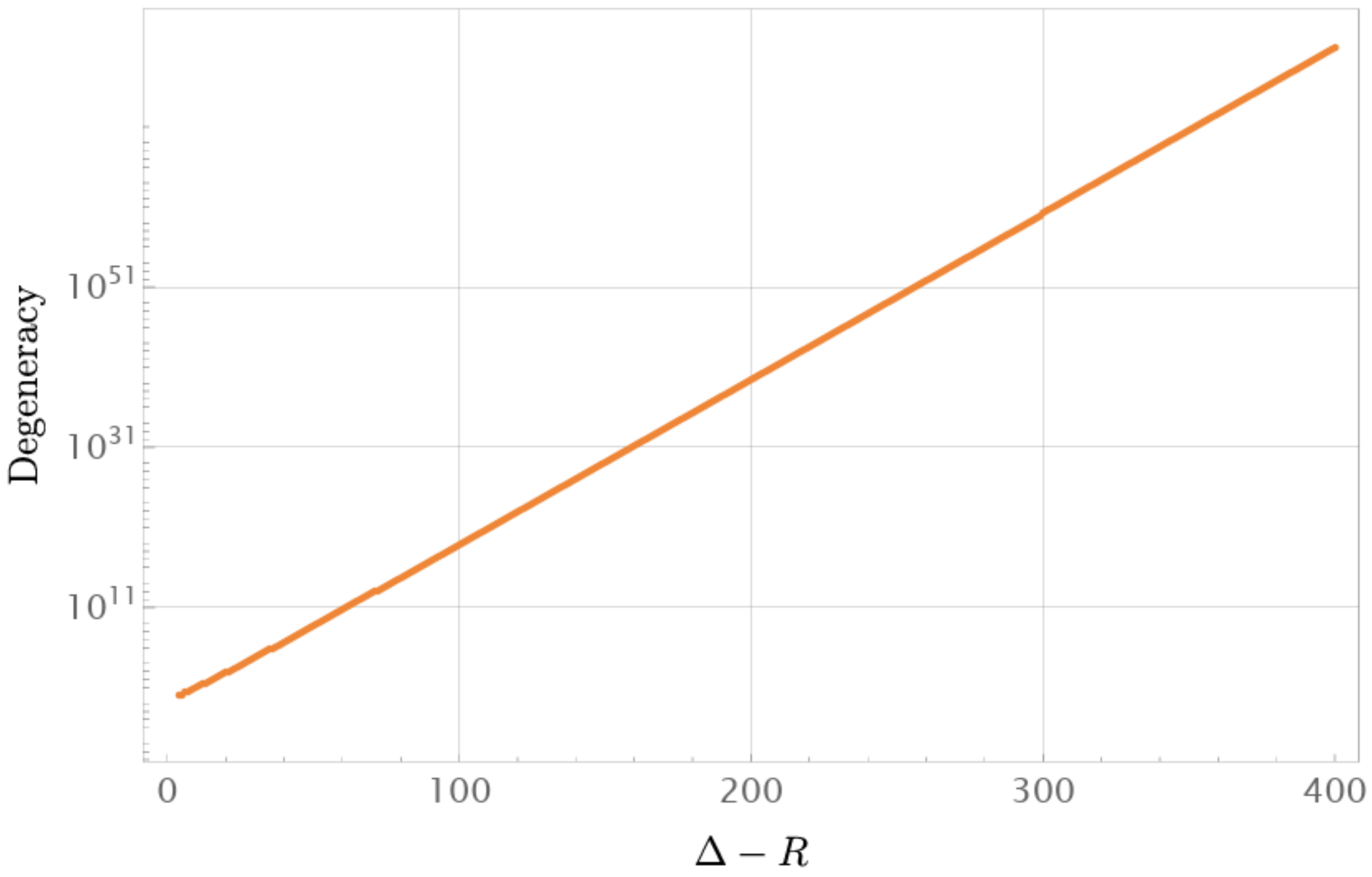
[Gadde,Pomoni,Rastelli'09]

# General mixed weak coupling limit

$$\mathcal{I} := \mathcal{I}^L(t,y,v) = \mathrm{Tr}(-1)^F t^{2(\Delta+j)} y^{2\bar{j}} v^{r-R}$$

[Mantegazza,Marchetto,Pomoni,Skrzypek,TW'26]

$$\Delta\mathcal{I} = \mathcal{I}_{\mathrm{SCQCD}} - \mathcal{I}_{\mathrm{inheri}} \neq 0$$




Observe:

**Exponential degeneracy for extra tower**

**Explicit identification of states possible via Hamiltonian - see paper**

## *Part II:*

# Boundedness theorems for Mordell-Weil groups

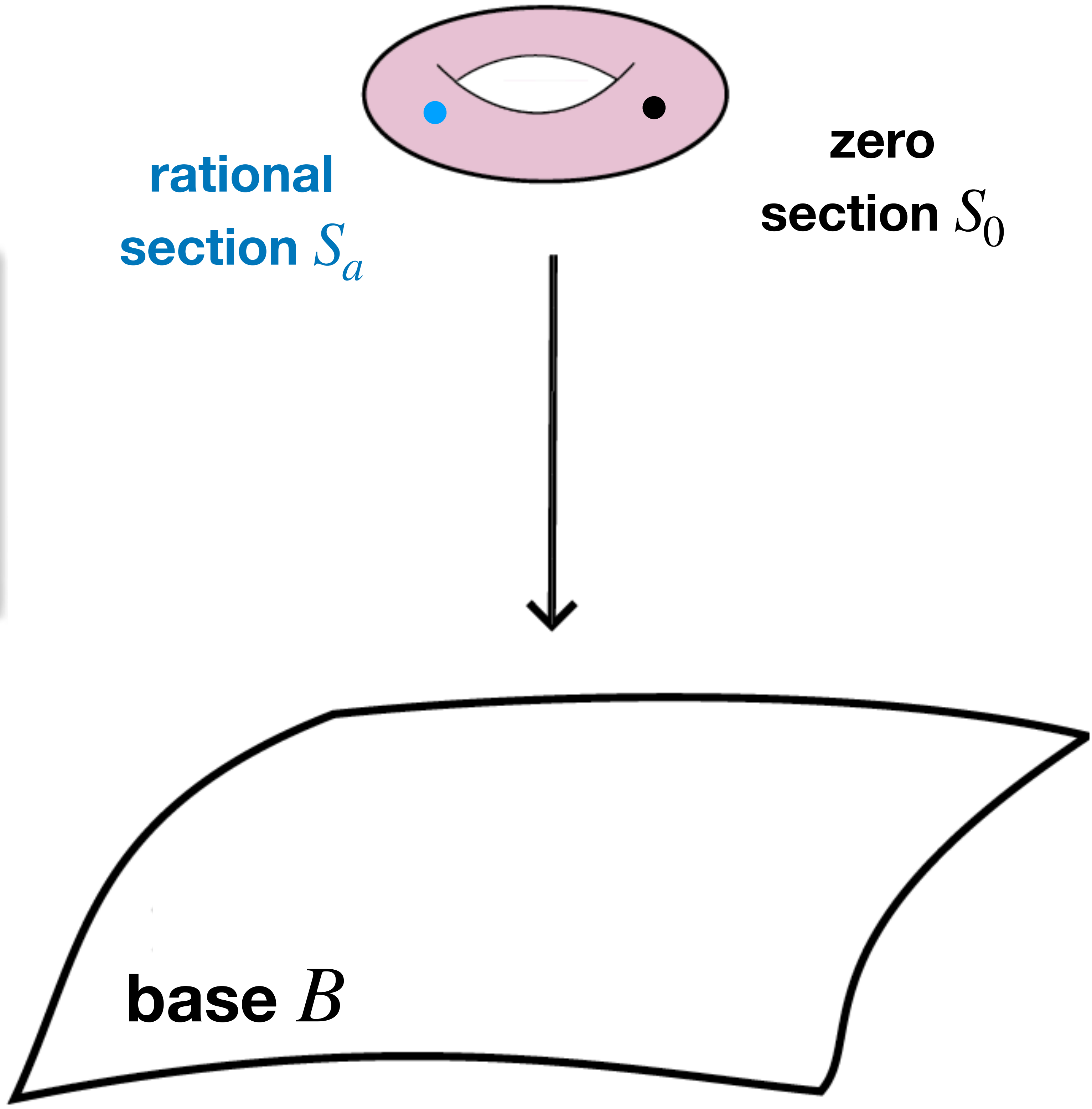
[Grassi,Paranjape,Miranda,Srinivas,TW'26]

# Abelian gauge groups and the Mordell-Weil group

Abelian part of the gauge group in F-theory on elliptic CY $X$

⟷

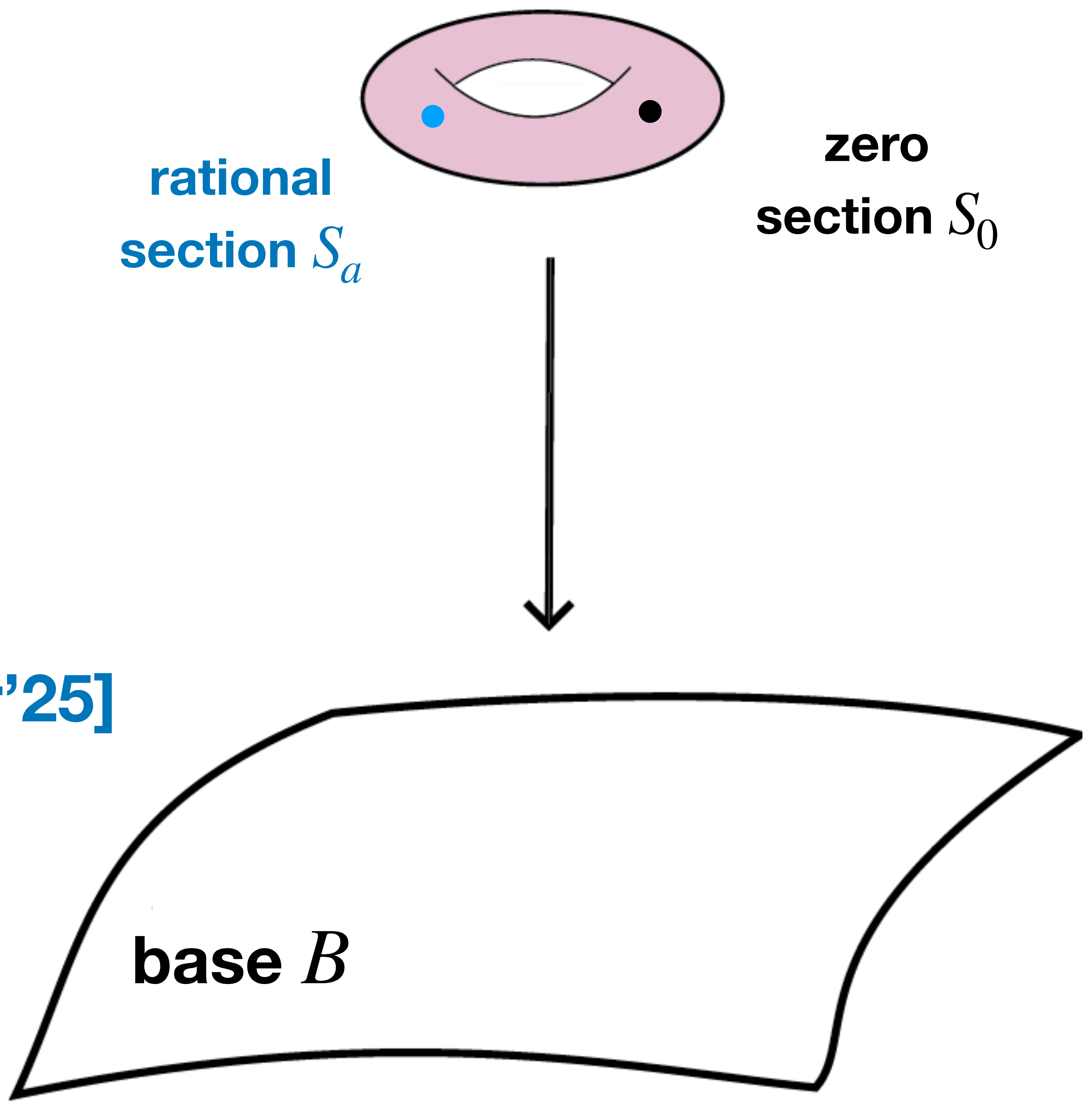
(Free part of) Mordell-Weil group of rational sections of $X$



# Abelian gauge groups and the Mordell-Weil group

Abelian part of the gauge group in F-theory on elliptic CY $X$ ⟷ (Free part of) Mordell-Weil group of rational sections of $X$

**Physics motivated bounds on abelian rank via probe strings**
of type introduced in **[Kim,Shiu,Vafa'19]**




- F-theory on elliptic CY3 (6d N=1): **[Lee,TW'19]**

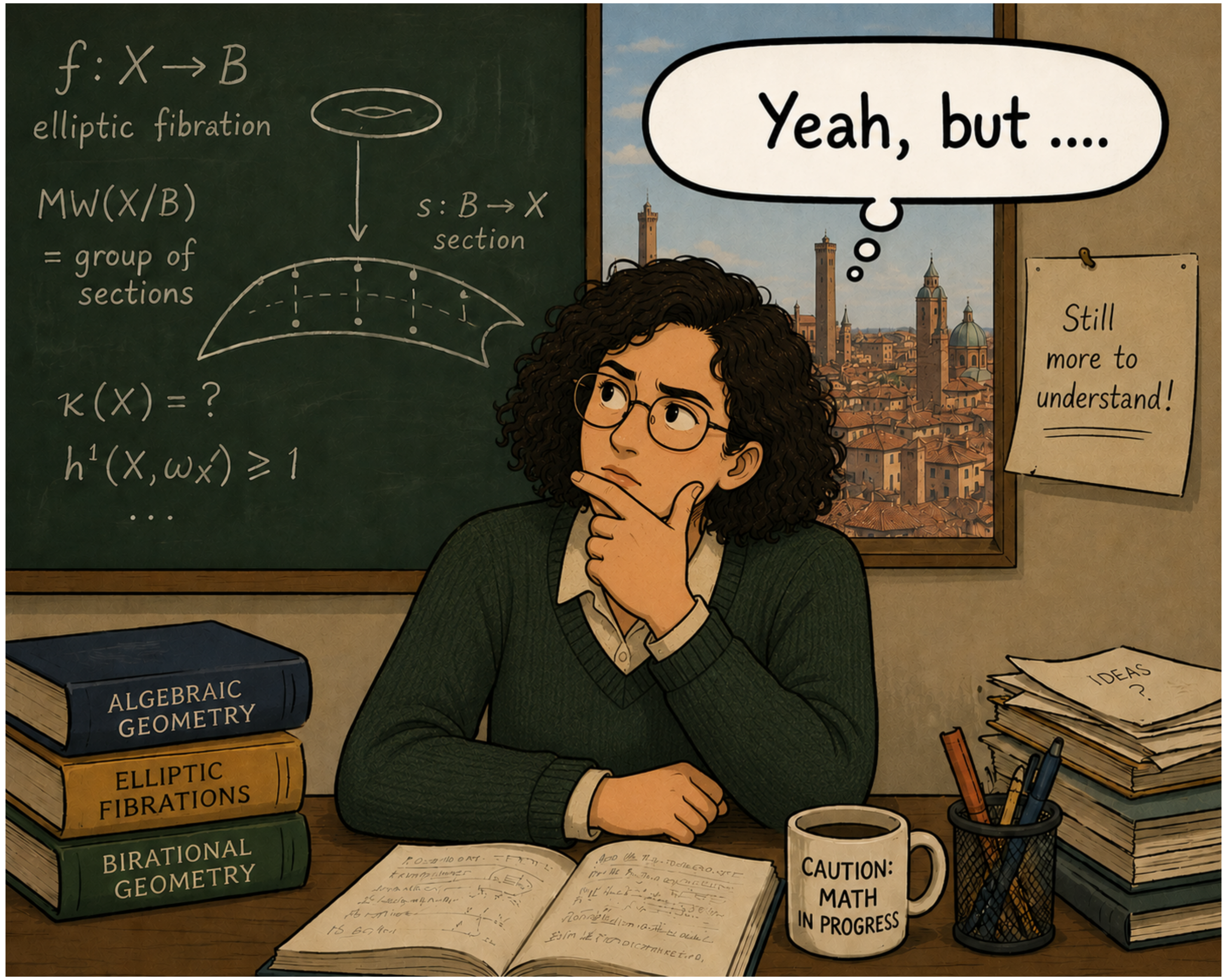
  $\mathrm{rk(MW)} \leq 32$ if $B = \mathbb{P}^2$
  $\mathrm{rk(MW)} \leq 20$ otherwise (improved to 18 in **[Lee,Oehlmann'22]**)
  see also **[Kim,Vafa,Xu'24] [Lee,Birkar'25]**

- F-theory on elliptic CY4 (4d N=1): **[Martucci,Risso,TW'22]**

  $\mathrm{rk(MW)} \leq 10\, C \cdot (-K_B) - 2$ if rational curve $C$ movable on $B$

# Abelian gauge groups and the Mordell-Weil group

## Physics motivated bounds on Mordell-Weil group rank via probe strings




*...*

*Mathematical proof?*

*Find universal bound for CY 4-folds?*

*Extend beyond 4-folds?*

*Extend beyond CY?*

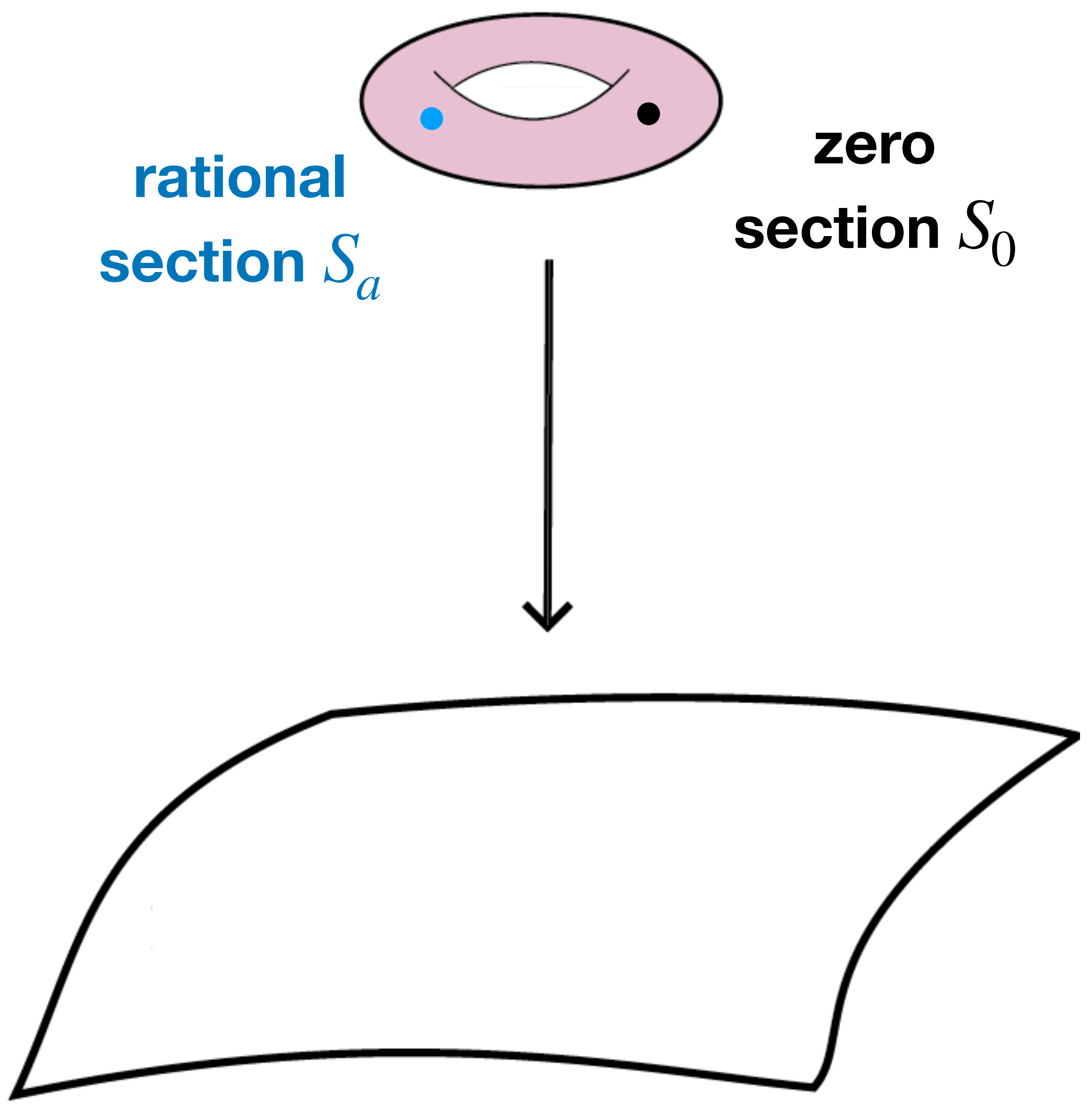
# Bounds on the Mordell-Weil group

$X$ : elliptic fibration, $\Lambda \neq 0$: discriminant divisor

[Grassi,Paranjape,Miranda, Srinivas,TW'26]

**Theorem 1:**
$X$ CY 3-fold: $\mathrm{rk}(\mathrm{MW}(X)) \leq 28.$

Similar bounds for certain classes of non-CY 3-folds, including those not covered by birational boundedness.




**Theorem 2:**
$X$ CY 4-fold: $\mathrm{rk}(\mathrm{MW}(X)) \leq 38$ if $B$ smooth (after birational trafo).

**Conjecture:** $X$ : CY $n$-fold: $\mathrm{rk}(\mathrm{MW}(X)) \leq 10\,n - 2$

# Bounds on the Mordell-Weil group

$X$ : elliptic fibration in any dimension, $\Lambda \neq 0$: discriminant $\mathbb{Q}$-divisor

**[Grassi,Paranjape,Miranda, Srinivas,TW'26]**

1) **Bound MW group of $X$ by MW group of surface $Z = \pi^{-1}(C)$**

see also **[Lee,Oehlmann'22]**

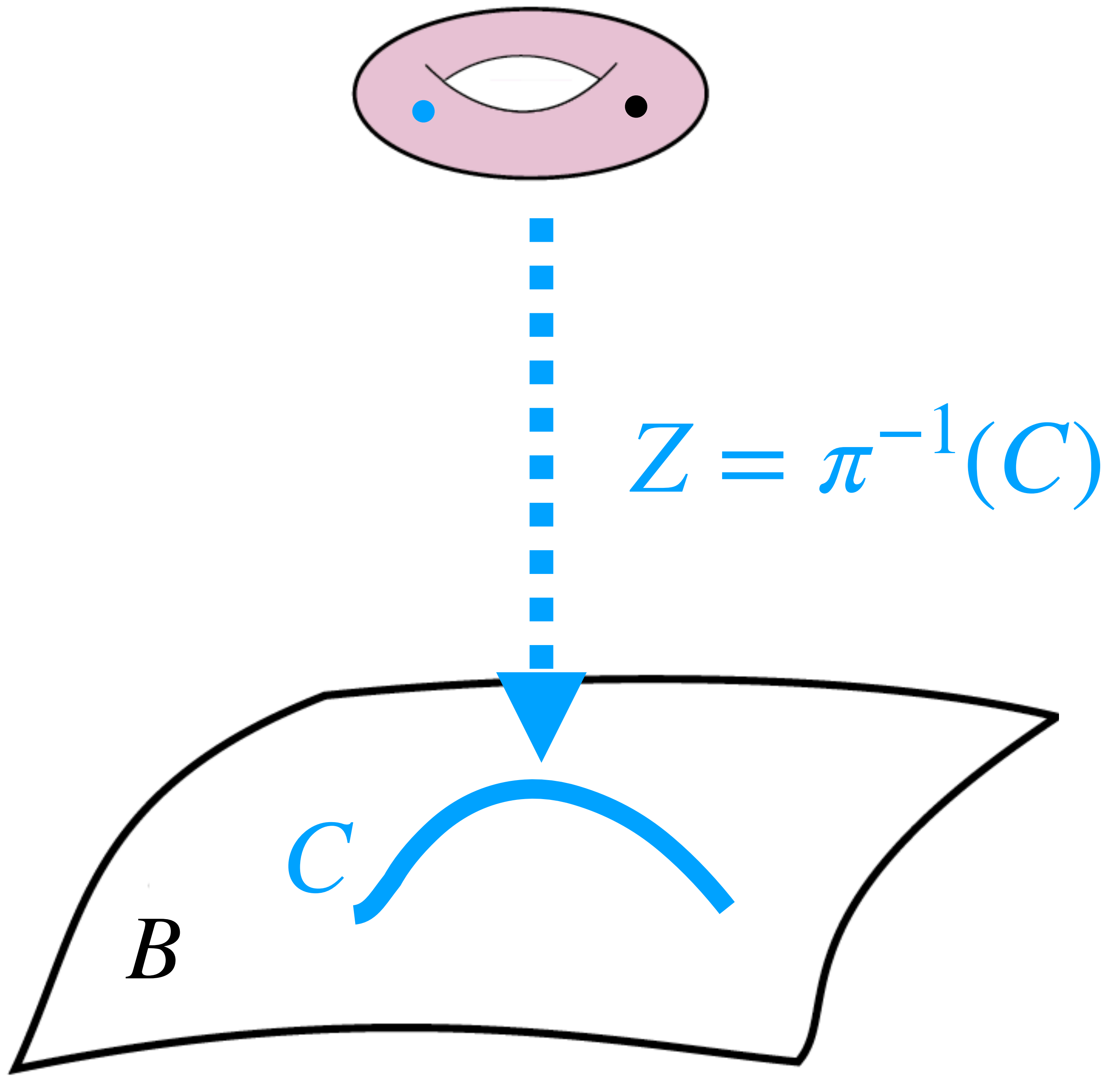
✓ possible in any dimension for suitable $C$

✓ no restrictions on $K_X$

↕

formalises probe string idea in physics:
Unitarity on string from M5-brane on $Z$ bounds d.o.f.

**[Kim,Shiu,Vafa'19] [Lee,TW'19] [Martucci,Risso,TW'22]**



# Bounds on the Mordell-Weil group

$X$ : elliptic fibration in any dimension, $\Lambda \neq 0$: discriminant $\mathbb{Q}$-divisor

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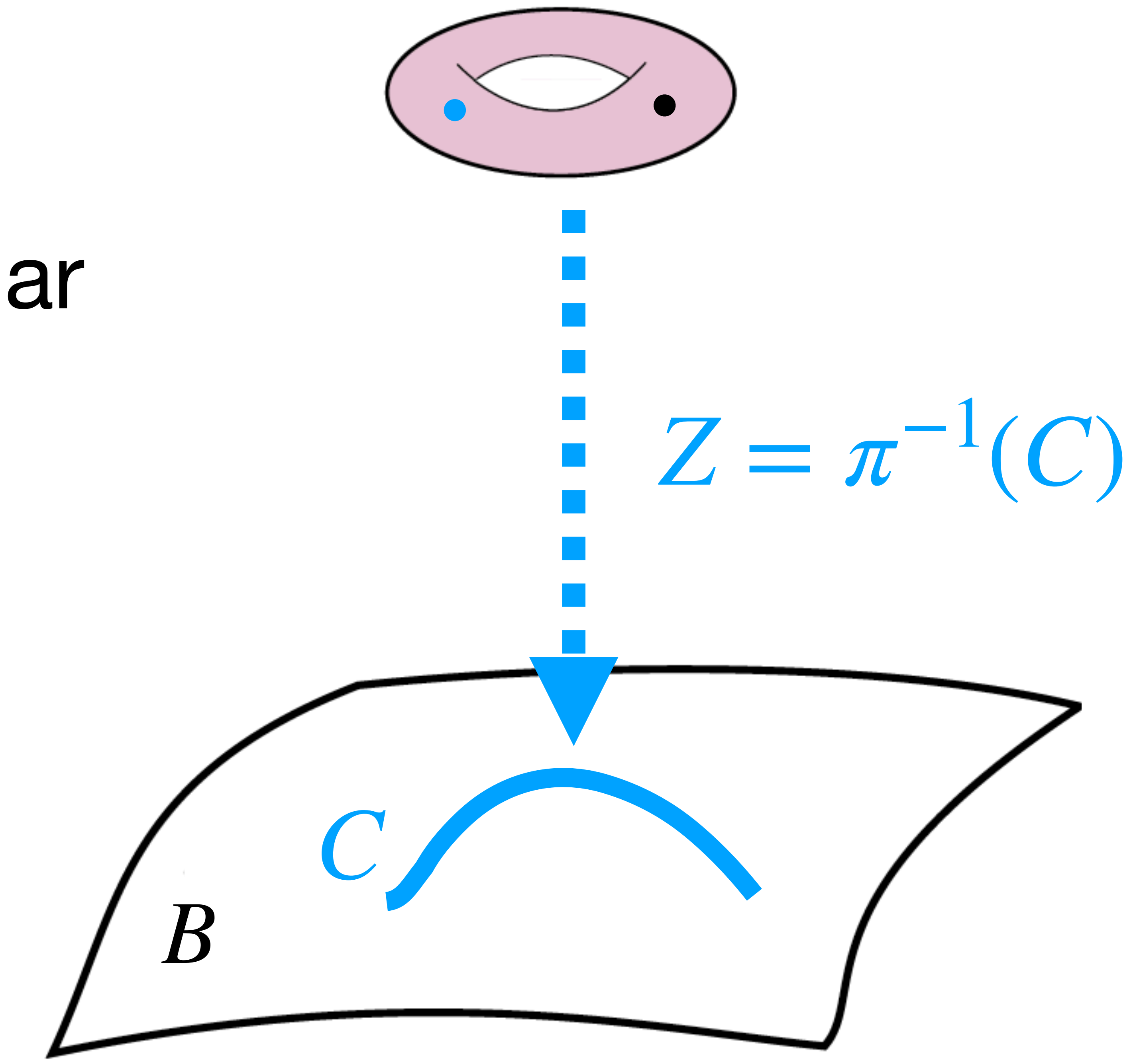
1) **Bound MW group of $X$ by MW group of surface $Z = \pi^{-1}(C)$**

see also [Lee,Oehlmann'22]

✓ possible in any dimension for suitable $C$ - even for $Z$ singular

✓ no restrictions on $K_X$




2) **Establish universal bounds by finding suitable $C$ / $Z$**

✓ practical restriction to CY and certain generalizations for which structure of $B$ and curves $C \subset B$ are known

# Bounds on the Mordell-Weil group

$X$ : elliptic fibration in any dimension, not only CY, $\Lambda \neq 0$: discriminant $\mathbb{Q}$-divisor

**1) Bound MW group of $X$ by MW group of surface $Z = \pi^{-1}(C)$**

**[Grassi,Paranjape,Miranda, Srinivas,TW'26]**

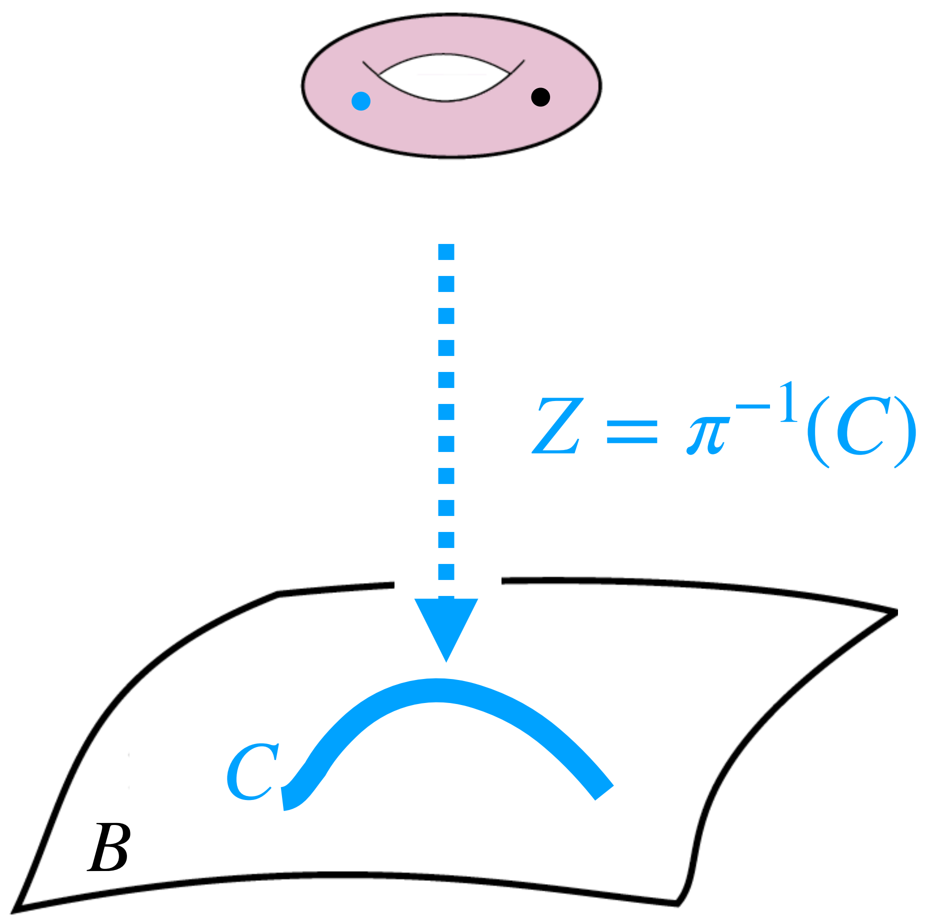
$C \subset B$: movable, smooth general curve with $\Lambda \cdot C > 0$

$C \subset B$: for | Pic($B$) = 1| $C \not\subset \Lambda$ smooth, general*

For $\pi^{-1}(C) = Z$, possibly singular:

$$\mathrm{MW}(X/B) \subseteq \mathrm{MW}(Z/C)$$

$$\Longrightarrow \mathrm{rk}(\mathrm{MW}) \leq 10\, C \cdot (-K_B) + 2g(C) - 2$$



# Bounds on the Mordell-Weil group

2) **Establish universal bounds by finding suitable $C\,/\,Z$**

[Grassi,Paranjape,Miranda, Srinivas,TW'26]

For $X \to B$ CY in any dimension*, $\Lambda \neq 0$

$B$ is (birationally) a Mori fiber space: $f : B \to U$, general fiber: Fano variety

**Calabi-Yau 3-fold:**

General fiber of $B$ is

- smooth $\mathbb{P}^1$ $\quad \mathrm{rk(MW)} \leq 18$
- smooth del Pezzo $\quad \mathrm{rk(MW)} \leq 28$

↕ for $B = \mathbb{P}^2$

**Calabi-Yau 4-fold:**

General fiber of $B$ is

- smooth $\mathbb{P}^1$ $\quad \mathrm{rk(MW)} \leq 18$
- smooth del Pezzo $\quad \mathrm{rk(MW)} \leq 28$
- Fano 3-fold, $|\mathrm{Pic}| = 1$ $\quad \mathrm{rk(MW)} \leq 38$

  if smooth: **17 possibilities**

↕ for $B = \mathbb{P}^3$

# Bounds on the Mordell-Weil group

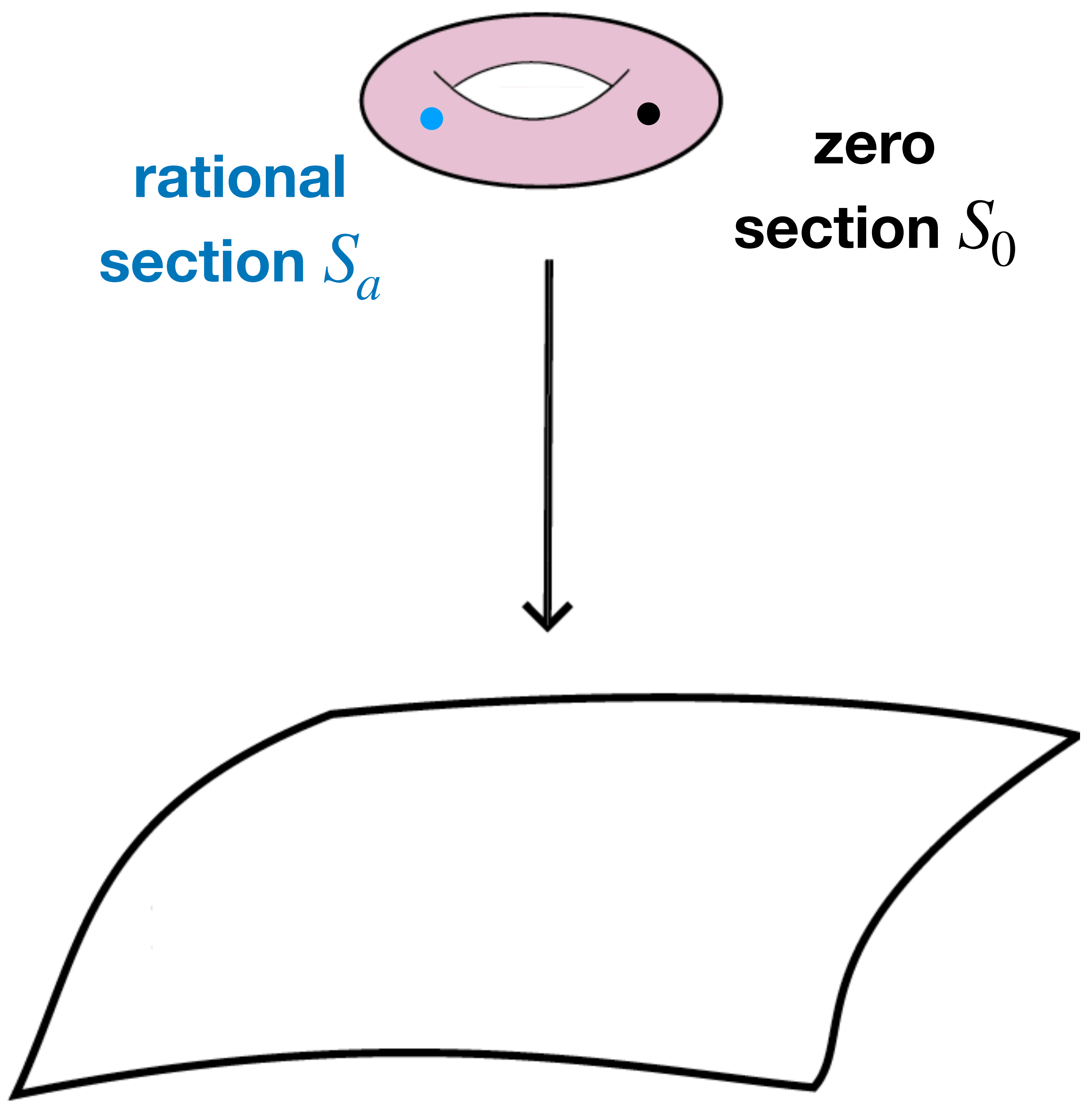
$X$ : elliptic fibration, $\Lambda \neq 0$: discriminant divisor

[Grassi,Paranjape,Miranda, Srinivas,TW'26]

**Theorem 1:**

$X$ CY 3-fold. $\mathrm{rk}(\mathrm{MW}(\mathrm{X})) \leq 28.$

Similar bounds for certain classes of non-CY 3-folds, including those not covered by birational boundedness.




**Theorem 2:**

$X$ CY 4-fold. $\mathrm{rk}(\mathrm{MW}(\mathrm{X})) \leq 38$ if $B$ smooth (after birational trafo).

**Conjecture:** $X$ : CY $n$-fold: $\mathrm{rk}(\mathrm{MW}(X)) \leq 10\,n - 2$

# Summary

## I) Partial weak coupling limits in AdS:

✓ Protected, strongly coupled exponential tower at AdS scale related to higher-spin tower via SUSY in N=2

✓ Recombination allows to trace back to critical 10 Type IIB superstring, though some of the dimensions seem to decouple in limit

→ non-critical, but gravitational / fundamental string

**Next step:** Generalisation to N=1 supersymmetry — work in progress

## II) Geometric proofs for bounds on MW ranks:

✓ New bounds for CY 4-folds: $\mathrm{rk(MW)} \leq 38$ for smooth base

✓ Generalizations beyond CY and - conjectured - to any dimension

# Summer School of the CRC 1624

## August 24—September 11, 2026

# Algebra and Geometry meets Quantum Fields and Strings

**University of Hamburg**
**Geomatikum**
Bundesstraße 55
20146 Hamburg

**Speakers:**

**Aug 24—28:**

**Lecture series by**
Sabin Cautis (The University of British Columbia)
Dustin Clausen (Institut des Hautes Études Scientifiques)
Pavel Etingof (Massachusetts Institute of Technology)
Melissa Liu (Columbia University)

**Colloquium talk by**
Pierrick Bousseau (University of Oxford)

**Aug 31—Sep 4:**

**Lecture series by**
Lara Anderson (Virginia Tech)
Tristan Collins (University of Toronto)
Clay Cordova (University of Chicago)
Michele Del Zotto (Uppsala University)
Nick Rozenblyum (University of Toronto)

**Colloquium talk by**
Ron Donagi (University of Pennsylvania)

**Sep 7 —11:**

**Lecture series by**
Laura Fredrickson (University of Oregon)
Marco Gualtieri (University of Toronto/UPC in Barcelona)
Boris Pioline (Laboratoire de Physique Théorique et Hautes Energies)
Ben Webster (University of Waterloo)

**Colloquium talks by**
Tomoyuki Arakawa (Kyoto University) and
John Francis (Northwestern University)

**Organizing Committee:**
Vicente Cortés, Craig Lawrie, David Reutter, Jörg Teschner, Timo Weigand

**Information and Registration:**